

Engineering Design File

Fate and Transport Modeling Results and Summary Report



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5. Summary: Fate and transport modeling was conducted to evaluate potential long-term concentrations in the Snake River Plain Aquifer that could result from transport of landfill constituents from the Idaho National Engineering and Environmental Laboratory Comprehensive Environmental Response, Compensation, and Liability Act Disposal Facility. Fate and transport simulations were conducted to identify contaminants of concern (COCs) with respect to meeting groundwater remedial action objectives (RAOs). Numerical modeling was performed using the Subsurface Transport Over Multiple Phases (STOMP) computer code to identify dilution/attenuation factors for a selected suite of contaminants. These factors were subsequently applied to the remaining contaminants in the facility design basis inventory to identify those contaminants that may pose a potential risk and to prepare RAO-based waste soil concentration limits. This report provides results and findings from fate and transport simulations.				
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ABSTRACT

This report describes the fate and transport modeling conducted to support the determination of remedial action objective-based waste soil concentrations for design basis contaminants intended for disposal at the INEEL CERCLA Disposal Facility. The modeling results provide contaminant travel time and concentration at the point of assessment for the 1,000-year facility design life and a 1,000,000-year evaluation period. The modeled concentrations are compared against the groundwater remedial action objective criteria. The results are intended to provide the methodology and starting point for adjusting design inventory concentrations resulting in the preliminary waste acceptance criteria for the complex. The results also support the evaluation of the design performance requirements of the INEEL CERCLA Disposal Facility final cover barrier.

TABLE

The following table gives a summary of the results of the experiments conducted during the summer of 1914. The table is arranged in four columns: the first column gives the name of the plant, the second column gives the date of the experiment, the third column gives the name of the person who conducted the experiment, and the fourth column gives the results of the experiment. The results are given in terms of the number of seeds that germinated and the number of plants that grew.

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ACRONYMS

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	contaminant of concern
DAF	dilution/attenuation factor
EDF	engineering design file
ELCR	excess lifetime carcinogenic risk
EPA	Environmental Protection Agency
HEAST	Health Effects Assessment Summary Tables
HI	hazard index
ICDF	INEEL CERCLA Disposal Facility
INEEL	Idaho National Engineering and Environmental Laboratory
IRIS	Integrated Risk Information System
MCL	maximum contaminant level
NCEA	National Center for Environmental Assessment
PNNL	Pacific Northwest National Laboratories
RAO	remedial action objectives
RBC	risk-based concentrations
RBL	risk-based level
RI	Remedial Investigation
ROD	Record of Decision
SRPA	Snake River Plain Aquifer
STOMP	Subsurface Transport Over Multiple Phases (transport modeling code)
WAG	waste area group



Fate and Transport Modeling Results and Summary Report

1. INTRODUCTION

The purpose of the contaminant transport simulations was to develop attenuation factors and travel time estimates for the contaminants of concern (COC) consistent with the facility design basis inventory presented in "INEEL CERCLA Disposal Facility Design Inventory" (EDF-ER-264).

Performance of fate and transport modeling is primarily driven by the requirements of the Record of Decision (ROD). The scope of the modeling effort was limited to the constituents presented in the design inventory. However, the simulations were performed in a manner that allows constituents not included in the design inventory to be easily included. The objectives of the modeling effort were as follows:

- To develop dilution/attenuation factors for use in evaluating travel times and resultant contaminant concentrations in groundwater at an assessment point downgradient of the Idaho National Engineering and Environmental Laboratory (INEEL) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Disposal Facility (ICDF) facility.
- To develop a set of waste soil concentration limits based on meeting the groundwater remedial action objectives (RAOs) of not exceeding maximum contaminant levels (MCLs) or risk-based concentrations (RBCs) in groundwater downgradient of the ICDF.
- To evaluate the effectiveness of the planned final cover for the ICDF by utilizing the anticipated cover infiltration rate as one of the inputs for the contaminant fate and transport model.
- To support development of waste acceptance criteria by providing the RAO-based soil concentrations.

Several hydrologic investigations and modeling studies have been conducted previously. The current modeling effort incorporates the previous information as well as results of site-specific data collection activities and facility-specific design parameters to provide an estimate of the transport scenarios in the vadose zone. Insufficient data exist to calibrate the model, especially considering the complexity of the vadose zone geology and other hydrologic features (e.g., the Big Lost River). The time duration of the model (1,000,000 years) is so great that the results for distant outyears contain a large degree of uncertainty. The information, however, appears adequate for the purposes of setting waste soil concentration limits and preliminary acceptance criteria, and evaluating the necessary effectiveness of the planned final cover.

Dilution attenuation factors (DAF) represent the ratio between the initial concentration of the contaminant in the waste and the resulting concentration in the aquifer at the assessment point. Travel time refers to the time elapsed from the placement of the waste in the ICDF to the arrival of the peak concentration of the contaminant at the assessment point. Travel time depends on the hydrologic properties of the porous media (e.g., infiltration rate, soil bulk density, porosity, and moisture content), the radiologic and environmental decay characteristics of the contaminants, and the adsorption characteristics of the contaminants as described by their distribution coefficient. There are more than 300 COCs, so fate and transport of eight surrogate contaminants representing the expected range of contaminant distribution coefficients (and thus contaminant travel times) were simulated. The surrogates

selected for the modeling and their respective distribution coefficients are shown in Table 1-1. Although the modeling effort contained in this document focuses on the design inventory constituents, additional constituents that have not previously been included in the design inventory can easily be included by utilizing this approach, if they are identified during remedial activities. Attenuation factors and travel time estimates for contaminants not specifically modeled may be estimated from the results of the surrogate with similar transport characteristics (K_d).

Table 1-1. Contaminant distribution coefficients and weighted averages for the different surrogates and model layer types.

Model Layer Type	Distribution Coefficient (K_d) (cm^3/g)							
	Surrogate							
	1	2	3	4	5	6	7	8
Aquifer Layer								
SRPA basalt	0	0	0.008	0.24	0.32	0.48	0.64	13.6
Vadose Zone Layer								
Basalt	0	0	0	0	0	0	0	0
Interbed	0	0	0.2	6	8	12	16	340
Alluvium	0	0	0.2	6	8	24	16	340
Clay	0	1	1	63	55	200	2,400	340
Operations layer	0	0	0.2	6	8	12	16	340
Waste	0	0	0.2	6	8	12	16	340
Weighted average ^a	0.00	0.006	0.058	1.95	2.426	4.464	18.592	91.12

- a. The weighted average vadose zone K_d is used only as an indicator of the relative mobility of specific contaminants in the vadose zone beneath the ICDF. The purpose of the weighted average K_d is to group constituents with similar distribution coefficients in the vadose zone with the appropriate surrogate. The weighted average K_d was computed by multiplying the fractional vadose zone thickness of each stratigraphic unit by the contaminant-specific K_d for each unit and summing the results.

The point of assessment was located in the upper portion (approximately 5 m) of the Snake River Plain Aquifer (SRPA) 20 meters (m) downgradient from the edge of the ICDF landfill surface barrier. The aquifer is approximately 76-m thick near the ICDF (Waste Area Group 3 Remedial Investigation Report). Previous modeling (Martian 2000) assumed an aquifer thickness equal to the assessment limit of 5 meters, but the Waste Area Group (WAG) 3 Remedial Investigation (RI) report indicates that assumption is unreasonably conservative based on the known thickness of the aquifer. For this simulation effort, the total aquifer thickness was specified as 76 m, although the groundwater contamination assessment interval was retained at 5 m thickness. This provides for a realistic aquifer thickness based on site-specific observation. Two recharge/infiltration rates were simulated to provide the range of expected results on the basis of barrier performance and background infiltration.

Existing hydrogeologic data and design specifications were used to provide input parameters for the fate and transport model. Sources of the data include previous modeling efforts (Martian 2000; Schafer et al. 1997), the Waste Area Group 3 Geotechnical Report (DOE-ID 2000), and input from the facility design requirements. Transport characteristics (distribution coefficients [K_d]) for the COCs were

previously inventoried for the vicinity of the ICDF (Jenkins 2001^a). The distribution coefficients are included in the contaminant-specific information presented in Appendices A and B for radiological and non-radiological contaminants, respectively.

Several assumptions were made during the modeling, and are listed below. The assumptions fall into two basic groups: assumptions related to the conceptual model and inputs to the model.

Assumptions related to the conceptual model include the following:

- It is assumed that there is no lateral flow or transport beyond the lateral boundaries of the model domain. This assumption forces all flow in the model downward until it reaches groundwater.
- There is no influence from the wastewater disposal ponds or the Big Lost River.
- Incorporation of the Big Lost River influence would decrease the peak concentration at the assessment point. The influence of the Big Lost River on contaminant transport to the SRPA was previously analyzed in site modeling performed for development of the conceptual design report (Martian 2000). It was determined to have the effect of decreasing contaminant time of travel to the aquifer but also decreasing the concentrations due to dilution.
- Seasonal fluctuations in recharge are annualized over the 1,000,000-year evaluation period.
- The cover functionally moderates the seasonal fluctuations in recharge.
- Absence of catastrophic geologic/hydrologic events that would disrupt the landfill and/or final cover.

Assumptions to input parameters to the model include the following:

- Continued integrity of the final cover to maintain recharge at the design infiltration rate of $1\text{E-}04$ m/yr (0.1 mm/yr) (EDF-ER-279).
- A cap efficiency of 99% was assumed.
- Precipitation not to exceed 300% of the historical precipitation as described in the hydrologic model of the final cover (EDF-ER-279).
- No limitations to initial solubility of constituents in the landfill.

^a Jenkins, T., DOE, letter to Martin Doornbos, BBWL, July 3, 2001, *K_d values for INTEC groundwater modeling (EM-ER-01-115)*.

2. FATE AND TRANSPORT MODELING METHODS

2.1 Modeling Approach

The following section describes the methods used to simulate the fate and transport of COCs identified for disposal at the ICDF. The two-dimensional (vertical and horizontal parallel to groundwater flow) numerical model used to simulate the contaminant transport from the ICDF was developed according to the conceptual model presented in the report describing the screening model results (Martian 2000) and additional information regarding the construction of the ICDF itself.

The modeling effort used the Subsurface Transport Over Multiple Phases (STOMP) version 2.0 finite difference code developed by Pacific Northwest National Laboratory (PNNL) to conduct the simulations. A description of the STOMP code is found in the Theory Guide (PNNL 1996) and the User's Guide (PNNL 2000). STOMP capabilities include, among others, the simulation of saturated and unsaturated flow regimes, transport of decaying and non-decaying contaminants, and transport of aqueous phase organic compounds. A complete description of STOMP capabilities and the actual equations and the partial differential approximations are contained within the Theory Guide and User's Guide, and the Applications Guide (Nichols et al. 2000) provides information regarding code validation. An evaluation of vadose zone model codes recently conducted at the Hanford Site (Mann et al. 1999) ultimately resulted in the selection of STOMP for simulating high-level radioactive tank waste fate and transport (Mann 2001^b). STOMP also includes aquifer fate and transport so that the vadose and aquifer portions of the modeling may be conducted within one model domain and simulation.

2.1.1 Modeling Analytical Equations and Numerical Calculations

Quantitative predictions of hydrogeologic flow and contaminant transport are generated from the numerical solution of non-linear partial differential equations that describe subsurface environment flow and transport phenomena. Simulating water and contaminant transport through the vadose zone requires the solution of the non-linear partial differential equations used to describe flow through unsaturated porous media. Solution of the equations requires moisture retention (aqueous phase pressure and moisture content) and fluid transport (hydraulic conductivity and moisture content or aqueous phase pressure) characteristic data for the porous media contained within the model domain. The model uses functional relationships (referred to as characteristic curves) to describe the characteristic data. The equation (1) used in the model (as presented in PNNL 1996) and shown below was developed by van Genuchten (van Genuchten et al. 1991) to describe the moisture retention characteristic of the porous media:

$$S_w = \left\{ 1 + \left(\alpha \left[\frac{P_g - P_w}{\rho_w g} \right]^n \right)^{-m} \right\} \quad \text{for } P_g - P_w > 0$$
$$S_w = 1 \quad \text{for } P_g - P_w \leq 0$$
(1)

Where

S_w = degree of water saturation of the porous media (dimensionless)

P_g = absolute pressure of the gas phase present (Pa, atmospheric pressure for these simulations)

^b Frederick Mann, CH2M HILL, to McMahon, William J., CH2M HILL, November 5, 2001, "Information regarding Request for Proposal," (STOMP Requirements).

P_w = absolute pressure of the water phase present (Pa)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

α (1/m), n , and m are curve fit parameters, and $m = 1 - 1/n$ except for basalt.

The Mualem equation (as presented in PNNL 1996 and shown below) was used to describe hydraulic conductivity as a function of moisture content:

$$k_{rw} = (S_w)^{1/2} \{1 - (1 - [S_w]^{1/m})^m\}^2 \quad \text{and} \quad K = k_{rw} * K_{sat} \quad (2)$$

Where

K = permeability (cm^2) or hydraulic conductivity (cm/s)

k_{rw} = relative permeability or hydraulic conductivity

K_{sat} = permeability (cm^2) or saturated hydraulic conductivity (cm/s)

S_w and m are defined as before.

Usually the m parameter determined from the saturation-capillary pressure relationship is also used in the Mualem relative hydraulic conductivity equation, but using a value of 1.9 (instead of $1 - 1/n$ or 0.778) provided a closer approximation of the linear relationship between saturation and relative hydraulic conductivity assumed in Magnuson (1993) and Schafer et al. (1997).

2.1.2 Model Calibration and Validation

Several hydrologic investigations have provided substantial information about the hydraulic characteristics of the vadose zone, but, as stated previously, insufficient data exist to calibrate a vadose model. To ensure comparability with previous efforts and investigations, the screening model and results (Martian 2000) provided a means of validating the STOMP model and modeling approach by comparison. A two-dimensional model using similar input as the screening model was constructed using STOMP. The STOMP model simulated the screening model described as possessing an attenuation barrier. To account for the side slopes of the ICDF landfill, the recharge was proportioned according to the increase in the ICDF area at ground surface. The screening model identified square bottom dimensions of 125 m, and square ground surface dimensions of 155 m. Thus, recharge through the ICDF in the STOMP model was proportioned by a factor of 1.5376 ($155 \text{ m} \times 155 \text{ m} / [125 \text{ m} \times 125 \text{ m}]$). Table 2-1 shows the comparison of the STOMP and the screening model results. The STOMP results compared well to the screening model results; in general, peak concentrations and arrival times were within 10%. This comparison indicates good correlation of both travel times and groundwater contaminant concentrations between the two simulations for the contaminants identified. As a further measure of validation, an analogous model using the semianalytical GWSCREEN was constructed and run for I-129. Results of the GWSCREEN model (discussed in Appendix A) were about 30% less than the STOMP results, which was considered acceptable given the conservative STOMP results and the differences in the two models' methodology.

Table 2-1. Comparison of STOMP and screening model results (EDF-ER-170 [Martian 2000]) with attenuation barrier at ICDF bounding inventory values^a.

			STOMP Results				Screening Model Results	
			Using Approximated TETRAD Brooks-Corey Basalt Saturation- Capillary Pressure Relationship		Using van Genuchten Basalt Saturation- Capillary Pressure Relationship		Using TETRAD Brooks- Corey Basalt Saturation- Capillary Pressure Relationship	
Contaminant			Peak Concen- tration (pCi/L)	Peak Arrival Time (Years)	Peak Concen- tration (pCi/L)	Peak Arrival Time (Years)	Peak Concen- tration (pCi/L)	Peak Arrival Time (Years)
Recharge Rate 1.0 cm/yr	I-129	I-129	65.4	561	63.8	581	64.8	600
		Np-237	57.4	14,348	56.1	15,348	59.5	15,450
		Tc-99	19,150	813	18,634	834	20,500	800
Recharge Rate 0.1 cm/yr	I-129	I-129	7.05	4,080	6.93	5,010	7.08	5,400
		Np-237	5.92	125,802	5.82	125,802	4.99	>100,000
		Tc-99	2,034	7,048	1,991	7,248	2,220	8,400

a. Model results for screening assessment point located 20 m downgradient from the edge of waste.

One complexity encountered in matching the screening model output was imitating in STOMP the hydraulic characteristics of the basalt layers in the screening model (TETRAD). The Brooks-Corey equation algorithm used in TETRAD to describe the basalt layers' moisture content (saturation)-capillary pressure relationship (and the assumed linear relationship between saturation and relative hydraulic conductivity) appears to be proprietary, and is not directly available in STOMP. However, the algorithm can be approximated in STOMP by calculating and tabulating saturation-capillary pressure values and interpolating between tabulated values. The results presented in Table 2-1 show that changing the saturation-capillary pressure relationship from the version of the Brooks-Corey equation in TETRAD to the van Genuchten equation (van Genuchten et al. 1991) resulted in little change in the peak concentration or peak arrival time.

Because the van Genuchten saturation-capillary pressure relationship is more widely available for vadose modeling than the version of the Brooks-Corey equation used in TETRAD (e. g., neither HYDRUS or STOMP include it, nor is that version of the Brooks-Corey equation contained in EPA/600/2-91/065 [1991]), the fate and transport simulations reported here used the van Genuchten equation to simulate the basalt moisture content (saturation)-capillary pressure relationship. The SRPA basalt and vadose basalt van Genuchten curve fit parameters were determined by approximating the saturation-capillary relationship shown in Figure 2-21 of Schafer et al. (1997) with Van Genuchten saturation-capillary pressure curves (Figure 2-1).

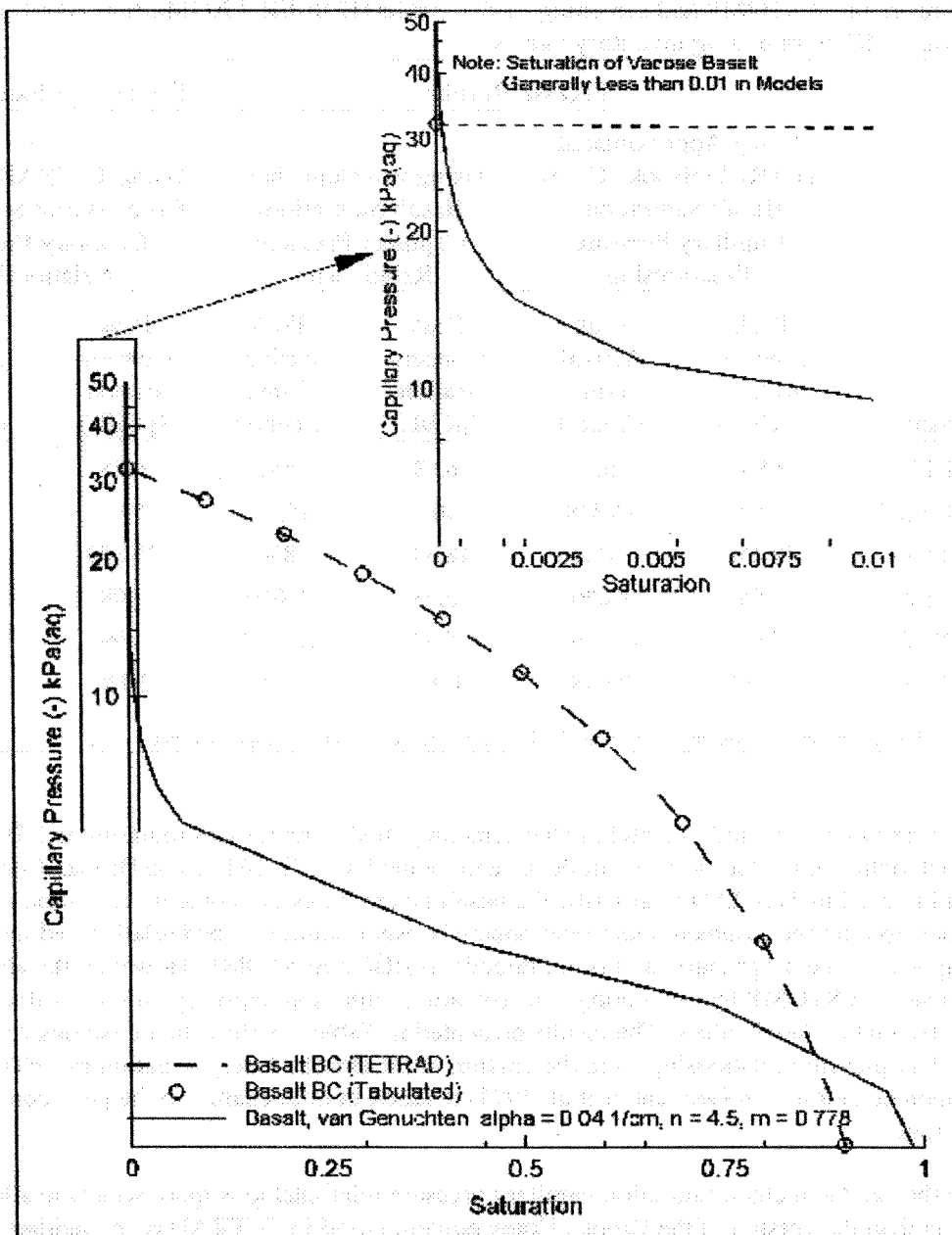


Figure 2-1. Comparison of the van Genuchten moisture content (saturation)-capillary pressure relationship to the TETRAD Brooks-Corey equation.

2.1.3 Model Construction

Figure 2-2 shows the revised conceptual model used to develop the numerical model grid (shown in Figure 2-3) and establish the model layers. Similar to the screening model, the numerical model only accounts for the vertical transport of moisture and contaminants in the vadose zone, and assumes that there is no influence from the wastewater disposal ponds or the Big Lost River. The influence of the Big Lost River on contaminant transport to the SRPA was previously analyzed in site modeling performed for development of the conceptual design report (Martian 2000). It was determined to have the effect of decreasing contaminant time of travel to the aquifer but also decreasing the concentrations due to dilution.

The length dimension of the ICDF landfill facility in the numerical model was determined from preliminary construction drawings (DOE-ID 2002) to be about 160 m in the direction parallel to groundwater flow. In the direction perpendicular to flow, the length dimension is about 194 m. The side slope of the landfill is ~3:1, so for the estimated waste volume (510,000 yd³ or 389,923 m³), the height of the trapezoidal waste volume is about 9.3 m. The slope of the sides increases the area at the top of the waste area to about 215.8 m by 249.8 m. Therefore, the contaminant transport portion of the modeling increased the specified recharge rate by a factor of ~ 1.74:1 (215.8 m × 249.8 m/[160 m × 194 m]). To maintain waste volume balance in the numerical model, the simulated waste height was adjusted to 12.56 m (389,923 m³/ [160 m × 194 m] ≈ 12.56 m). The model domain represented a vertical cross-section of the ICDF waste area and operations area, the clay liner, and the vadose zone. The groundwater domain included 58 m to the edge of the surface barrier and 20 m to the assessment point within the upper portion (approximately 5 m) of the SRPA.

Tables 2-2 and 2-3 present the soil hydraulic and contaminant transport parameters of the different layers used in the model and the source of the information. In general, parameters developed in previous models (e.g., Schafer et al. 1997; Martian 2000) were carried forward except where new data were available. The site geotechnical report (DOE-ID 2000) and recent drilling during November 2001 provided substantial new information and data about the lower alluvium unit present near the ICDF site, and the design specifications provided new information regarding the clay, operations layer, and waste layer. For all layers, the saturated moisture content was assumed to equal the porosity. Synthetic materials that are part of the liner design (e.g., polymer membranes, etc.) were not included in the model stratigraphy.

The hydrologic and contaminant fate and transport modeling was conducted in two steps (see Appendix E for STOMP input parameters). The first step involved inputting background hydrologic boundary conditions and calculating the steady-state solution for water content and capillary pressure. The upper boundary received constant infiltration equal to 0.01 m/yr (1 cm/yr), and the sides of the model in the vadose zone allowed no flow or contaminant transport to occur across those boundaries. The upgradient aquifer boundary received a constant flux of 0.06 m per day (m/day), which equates to a flow velocity of 1 m/day. The downgradient aquifer boundary was fixed to a constant hydraulic head such that the head at the assessment point equaled approximately 5 m. The background hydraulic boundary conditions were comparable to those presented in Martian (2000). In the second step, the output solution of the steady-state simulation was used as the input starting condition for the contaminant transport simulations. Figure 2-4 shows the residual moisture content of the STOMP simulation.

Table 2-2. Summary of soil properties and moisture content (saturation)-aqueous pressure relationship curve fit parameters.

Model Layer Type	Saturated Moisture Content	Residual Moisture Content	Curve Fit Parameter α (1/m)	Curve Fit Parameter n	Curve Fit Parameter m
SRPA basalt ^a	0.06	0.0002	4.0	4.50	0.778 / 1.9
Basalt	0.05	0.0002	4.0	4.50	0.778 / 1.9
Interbed ^b	0.487	0.142	1.066	1.523	0.343
Alluvium ^c	0.424	0.142	0.595	1.09	0.083
	[0.487] ^d		[1.066] ^d	[1.523] ^d	[0.343] ^d
Clay ^e	0.39	0.07	0.800	1.108	0.097
	[0.4] ^d				

Table 2-2. (continued).

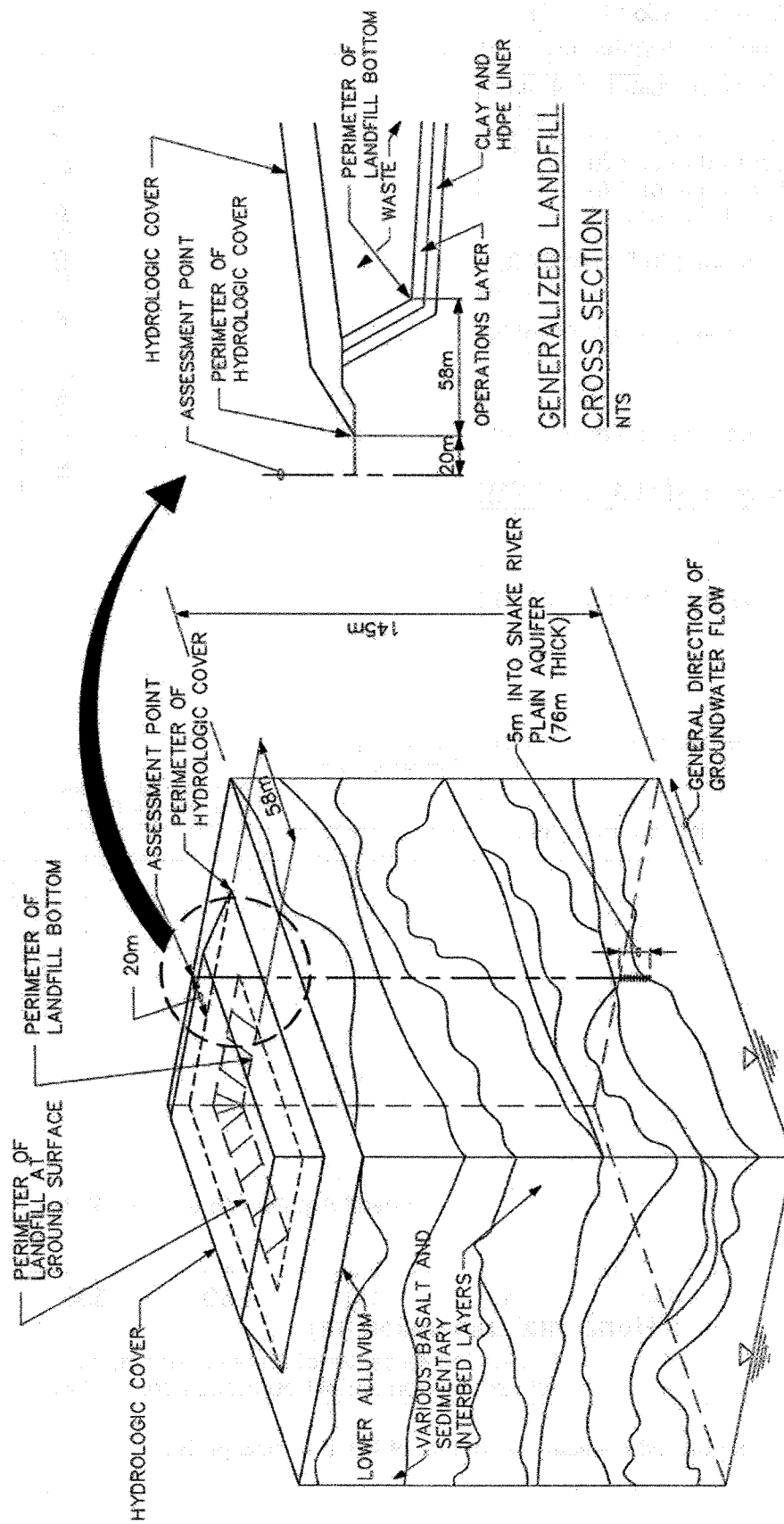
Model Layer Type	Saturated Moisture Content	Residual Moisture Content	Curve Fit Parameter α (1/m)	Curve Fit Parameter n	Curve Fit Parameter m
Operations layer ^f	0.275 [0.487] ^d	0.083 [0.142] ^d	1.066	1.523	0.343
Waste ^f	0.266 [0.487] ^d	0.072 [0.142] ^d	1.066	1.523	0.343

- a. Basalt curve fit parameters moisture content parameters are reported in Schafer et al. 1997, and curve fit parameters are estimated from moisture content/pressure relationship in Schafer et al. 1997. Basalt parameter m is 0.778 for saturation-capillary pressure relationship, and 1.9 for saturation-relative hydraulic conductivity relationship.
- b. Interbed moisture content and curve fit parameters are reported in Schafer et al. 1997.
- c. Alluvium parameters are determined from site geotechnical report (DOE-ID 2000), except the residual moisture content (no data reported).
- d. Values used in the screening model (Martian 2000) are shown in brackets where different.
- e. Clay saturated moisture content is based on design specifications; residual moisture content and curve fit parameters are reported in EDF-ER-170 (Martian 2000).
- f. Operations and waste layers saturated and residual moisture content parameters are based on design specifications; curve fit parameters are reported in EDF-ER-170 (Martian 2000). These moisture layer parameters differ due to different compaction levels.

Table 2-3. Summary of soil hydraulic and contaminant transport properties.

Model Layer Type	Bulk Density ^a (kg/m ³)	Saturated Hydraulic Vertical Conductivity ^b (cm/s)	Longitudinal Dispersivity ^c (m)	Transverse Dispersivity ^c (m)
SRPA basalt	2491	2.6e - 04 ^d	6	3
Basalt	2518	2.6e - 04 ^d	5	0
Interbed	1359	6.7e - 05	5	0
Alluvium	1526	6.7e - 08	5	0
Clay	1586	1e - 07	5	0
Operations layer	1922	1e - 04	5	0
Waste	1946	1e - 03	5	0

- a. Bulk density is determined from the saturated moisture content and assumed particle solid density of 2,650 kg/m³, except for alluvium with bulk density values reported in the site geotechnical report (DOE-ID 2000), and the clay with a design particle solid density of 2,600 kg/m³.
- b. Saturated hydraulic conductivity values are reported in EDF-ER-170 (Martian 2000), except for alluvium with values reported in DOE-ID 2000, and basalt with values reported in Schafer et al. 1997.
- c. Longitudinal and transverse dispersivity values are reported in EDF-ER-170 (Martian 2000).
- d. Basalt saturated horizontal hydraulic conductivity = 7.7e-02 cm/sec.



GENERAL HYDROGEOLOGIC
CHARACTERIZATION FOR
FATE AND TRANSPORT (STOMP) MODEL

Figure 2-2. Conceptual model of ICDF vertical profile.

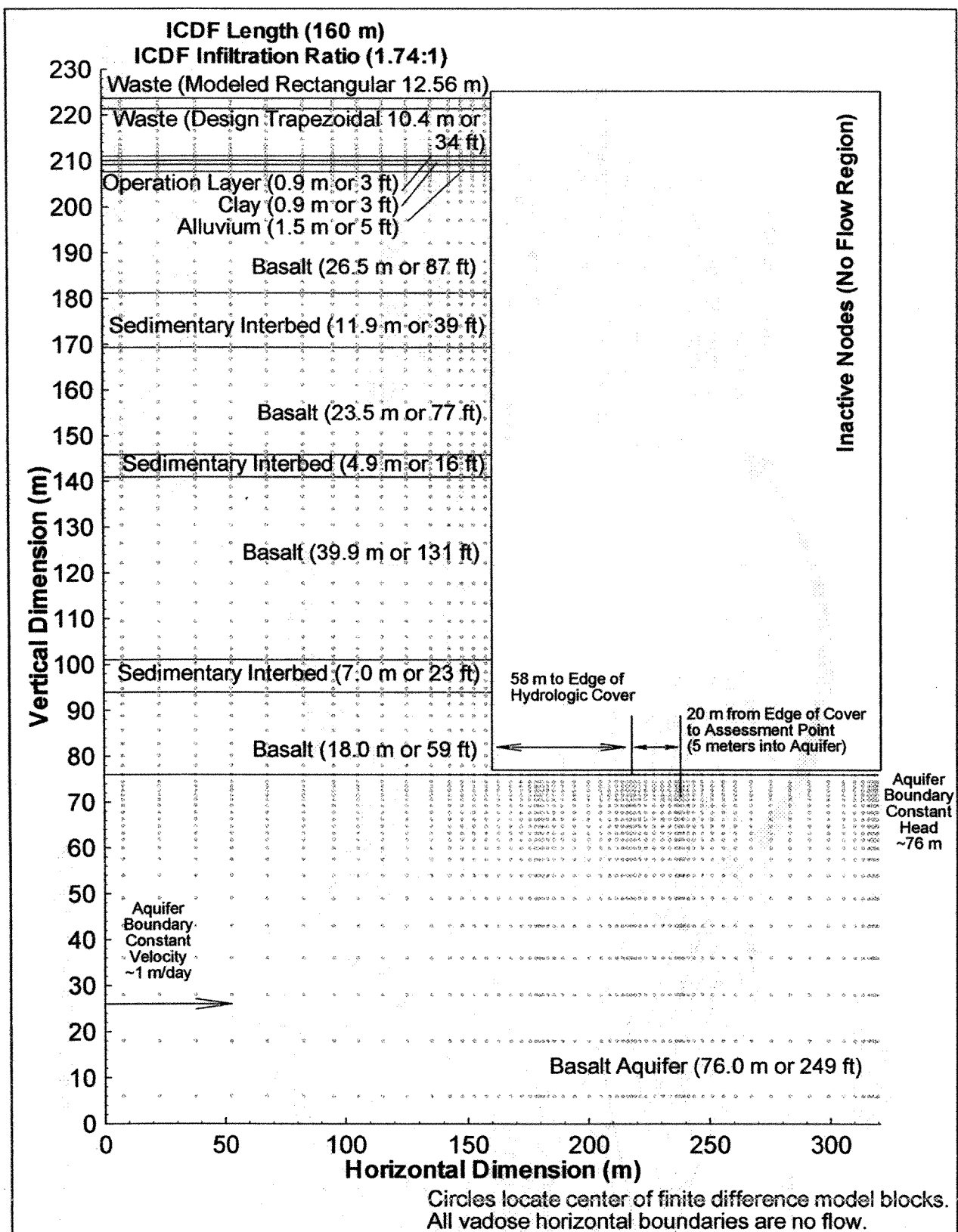


Figure 2-3. Numerical model grid and boundary conditions of ICDF vertical profile.

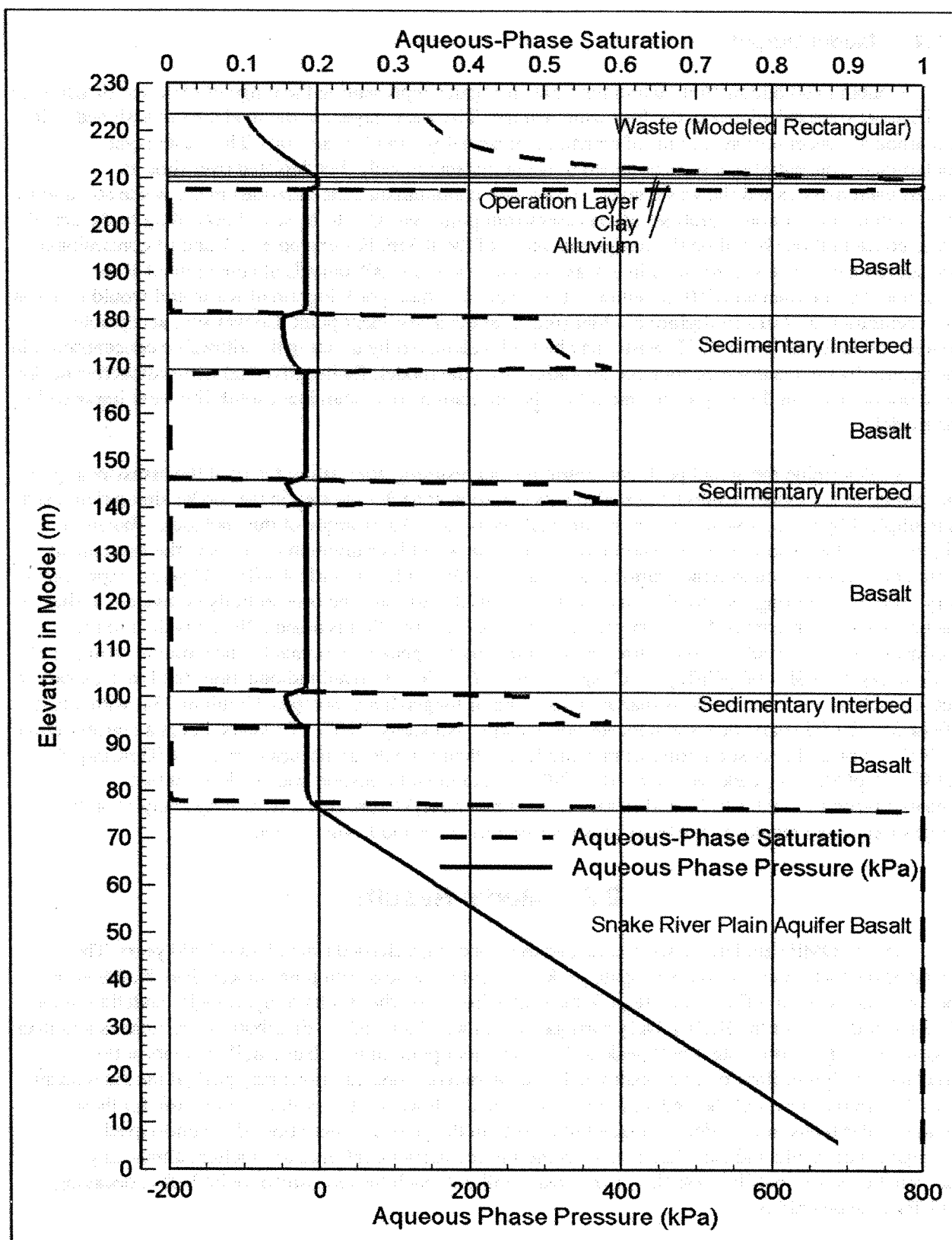


Figure 2-4. Residual moisture and capillary pressure initial conditions for transport simulations using STOMP.

2.1.4 Model Output

Contaminant attenuation factors for eight surrogates representing the range of expected distribution coefficients were calculated in the following manner. The waste layers of the model were assigned unit contaminant concentrations (1 unit of contaminant per kilogram of waste soil). The waste layer contaminant concentrations were assumed to occur instantaneously, but depleted over time as contaminant mass exited the waste layers. Using unit contaminant concentrations in the waste soil allows the resulting aquifer concentrations at the assessment point (units/L) to be scaled according to the actual waste concentrations based on the design inventory of the ICDF. For example, if 1 unit of contaminant per kilogram of waste soil resulted in a peak concentration of 0.005 units/L of contaminant at the assessment point, then an ICDF inventory of 3 mg contaminant per kilogram of waste soil would result in a concentration of 0.015 milligram per liter (mg/L) at the assessment point. Conversely, acceptable concentration limits in the ICDF waste may be back-calculated by dividing the allowable concentration in the aquifer by the resulting aquifer concentration from the model. Radioactive and non-radioactive decay were not included in this step of the modeling. No limitations to contaminant solubility were imposed by the model.

To determine the actual peak concentration and resulting attenuation factor at the assessment point (according to the model results), the scaled concentration at each time step in the model simulation result is multiplied by the radioactive or environmental decay rate. An example of this method is shown in Figure 2-5, which shows the concentration of surrogate 4 and four uranium isotopes at the assessment point at the design recharge/infiltration rate. Uranium-238, with a half life $4.47\text{E} + 09$ years, experiences very little decay during the simulation period, and thus the arrival time is essentially equivalent to that of the undecayed surrogate ($8.52\text{E} + 05$ years). The peak concentration is essentially equivalent to the product of design inventory concentration multiplied by the peak contaminant concentration ratio ($1.95\text{E} + 03 \text{ pCi/kg} * 3.43\text{E} - 06 \text{ pCi/L per pCi/kg} = 6.69 \text{ pCi/L}$). Shorter-lived radionuclides tend to peak earlier but at much lower concentrations than non-decaying or longer-lived isotopes. Uranium-234, with a half-life of $2.45\text{E} + 05$ years, peaks in concentration in approximately $5.23\text{E} + 05$ years, but at a concentration ($3.26\text{E} - 03 \text{ pCi/L}$) almost an order of magnitude less than if no decay occurred ($6.03\text{E} + 03 \text{ pCi/kg} * 3.43\text{E} - 06 \text{ pCi/L per pCi/kg} = 2.07\text{E} - 02 \text{ pCi/L}$). Contaminant transport was modeled at two recharge/infiltration rates (0.01 and 0.0001 m per year [m/yr]) to provide a sensitivity analysis on the range of expected results on the basis of barrier performance and having no barrier.

2.2 Model Results

The STOMP simulations were extended to a maximum elapsed time of 1,000,000 years. The results show that no undecayed surrogate peaks reached the assessment point in less than 30,000 years at the maximum design infiltration rate of 0.0001 m/yr (based on the results of hydrologic modeling of the final cover design for the ICDF). Only surrogates with weighted vadose distribution coefficients less than or equal to that of Surrogate 4 will peak at the assessment point in less than 1 million years at the maximum design infiltration rate. Radionuclide contaminant concentrations may peak at the assessment point before the arrival of the undecayed surrogate peak. However, the peak concentration for these radionuclides tends to be orders of magnitude less than the peak concentration of the undecayed surrogate. The results indicate that as long as the surface barrier continues to function, almost any radionuclide with a half life less than 1,000 years will not reach the assessment point before decaying to undetectable quantities.

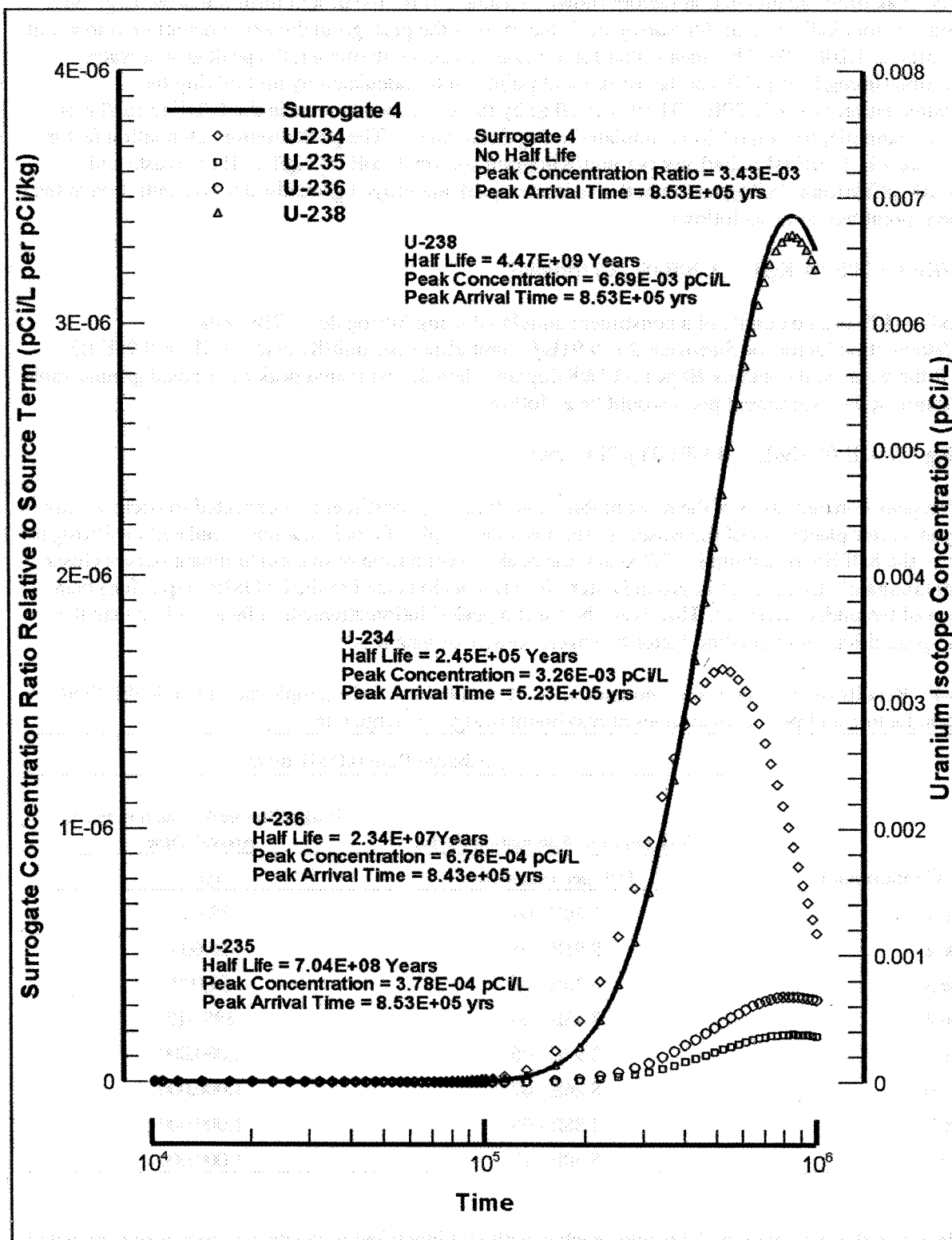


Figure 2-5. Example contaminant arrival curves at the assessment point for Surrogate 4 and three uranium isotopes at the design recharge/infiltration rate.

The peak dilution/attenuation factors shown in Table 2-4 for the design infiltration/recharge rate. These peak factors indicate that, for Surrogate 1, the ratio of the peak groundwater concentration to a unit concentration is $1.20\text{E} - 04$. This means that for a non-decaying contaminant, the peak groundwater concentration (in mg/L or pCi/L) at the assessment point can be calculated by multiplying the dilution/attenuation factor ($1.20\text{E} - 04$ 1/L per 1/kg) by the soil concentration in the ICDF in mg/kg or pCi/kg. For example, tritium (H-3) is simulated using Surrogate 1. The peak dilution/attenuation factor for Surrogate 1 is $1.20\text{E}-04$ units/Liter per unit/Kilogram soil (or $1.20\text{E}-04$ Kg/L). If the waste soil contains 100 pCi tritium /Kilogram, then the estimated peak undecayed groundwater concentration at the assessment point would be as follows:

$$100 \text{ pCi/Kg} * 1.20\text{E}-04 \text{ Kg/L} = 1.20\text{E}-02 \text{ pCi tritium/L}$$

Iodine-129 is an example of a constituent simulated using Surrogate 2. The peak dilution/attenuation factor for Surrogate 2 is $9.91\text{E}-05$ units/Liter per unit/Kilogram soil (or $9.91\text{E}-05$ Kg/L). If the waste soil contains 20 pCi I-129/Kilogram, then the estimated peak undecayed groundwater concentration at the assessment point would be as follows:

$$20 \text{ pCi/Kg} * 9.91\text{E}-05 \text{ Kg/L} = 1.98\text{E}-03 \text{ pCi I-129/L}$$

The peak concentration of the most mobile non-decaying constituents is expected to occur at least 32,605 years after placement of the waste. Tritium is an example of a radionuclide simulated by Surrogate 1. Because the half life of tritium is 12.3 years, the peak concentration of that contaminant occurs closer to the contaminant's first arrival in groundwater (70 years, as indicated in the STOMP output file) than the arrival of the undecayed peak. However, the tritium peak dilution/attenuation factor is less than the surrogate peak dilution/attenuation factor by several orders of magnitude.

Table 2-4. Results of surrogate contaminant transport simulations and example radionuclide dilution/attenuation factors and peak arrival times at maximum design recharge rate.

Contaminant	Recharge Rate 0.0001 m/yr	
	Peak Dilution/Attenuation Factor	Peak Dilution/Attenuation Factor
	(1/L per 1/kg soil)	Arrival Time (yrs)
Surrogate 1	$1.20\text{E} - 04$	32,605
Surrogate 2	$9.91\text{E} - 05$	36,605
Surrogate 3	$6.33\text{E} - 05$	59,007
Surrogate 4	$3.43\text{E} - 06$	895,312
Surrogate 5	$2.97\text{E} - 06$	1,000,000
Surrogate 6	$8.26\text{E} - 07$	1,000,000
Surrogate 7	$4.88\text{E} - 08$	1,000,000
Surrogate 8	$5.50\text{E} - 17$	1,000,000

Based on the surrogate model results, each constituent identified in the design inventory is modeled using the representative surrogate dilution/attenuation factors (see Appendix B). The appendix continues on by evaluating the constituent concentrations in groundwater as compared with the RAOs. The methodology and results of the process are presented in Appendix B. The calculation for risk-based concentrations (RBC) is presented in Appendix C.

Table 2-5 presents the results of the contaminant transport modeling of peak arrival time and peak concentration for the two simulated recharge rates. By using the dilution/attenuation factor derived from the simulations and the design inventory concentrations, the estimated assessment point peak concentration of the COC can be calculated for all COCs. Table 2-5 contains the results of a subset of the total list of COCs.

Table 2-5. Results of selected contaminant transport simulations at maximum design recharge rate (0.0001 m/yr) scaled to ICDF inventory.

Constituent		Half-Life (years)	Design Inventory Concentration (C_{DI}) (pCi/kg or mg/kg)	Peak Concentration (pCi/L or mg/L)	Peak Concentration Arrival Time (years)
H 3	Surrogate 1	1.24E + 01	4.96E + 04	2.15E - 08	1.00E + 02
Sulfate	Surrogate 1	NA	2.05E + 01	2.46E - 03	3.13E + 04
Sulfide	Surrogate 1	NA	7.59E + 02	9.10E - 02	3.13E + 04
Tributylphosphate	Surrogate 1	1.16E + 00	3.64E - 01	4.36E - 05	3.03E + 04
I129	Surrogate 2	1.57E + 07	1.30E + 03	1.28E - 01	3.33E + 04
Benzene	Surrogate 2	1.00E + 00	6.03E - 01	5.66E - 25	5.84E + 01
Toluene	Surrogate 2	4.20E - 02	9.82E - 01	8.12E - 190	2.76E + 01
Tc 99	Surrogate 3	2.13E + 05	5.76E + 03	3.04E - 01	5.40E + 04
Xylene (total)	Surrogate 3	7.12E - 02	3.45E + 00	2.21E - 50	5.84E + 01
Boron	Surrogate 3	NA	1.85E + 02	1.17E - 02	5.80E + 04
U234	Surrogate 4	2.45E + 05	6.03E + 03	3.26E - 03	5.13E + 05
U235	Surrogate 4	7.04E + 08	1.10E + 02	3.78E - 04	8.43E + 05
U236	Surrogate 4	2.34E + 07	2.02E + 02	6.76E - 04	8.33E + 05
U238	Surrogate 4	4.47E + 09	1.95E + 03	6.69E - 03	8.33E + 05
Np237	Surrogate 5	2.14E + 06	6.43E + 02	1.38E - 03	9.13E + 05
Dibenzofuran	Surrogate 5	4.79E - 02	3.24E - 01	0.00E + 00	NA
Molybdenum	Surrogate 5	NA	1.02E + 01	3.02E - 05	1.00E + 06
K-40	Surrogate 5	1.28E + 09	1.92E + 03	5.69E - 03	1.00E + 06
Sr90	Surrogate 6	2.91E + 01	2.29E + 07	0.00E + 00	NA
Cadmium	Surrogate 6	NA	3.59E + 00	2.96E - 06	1.00E + 06
Co-60	Surrogate 6	5.27E + 00	1.93E + 05	0.00E + 00	NA
Cobalt	Surrogate 6	NA	6.04E + 00	4.99E - 06	1.00E + 06
Sodium	Surrogate 7	NA	2.11E + 02	1.03E - 05	1.00E + 06
Pu238	Surrogate 7	8.77E + 01	2.33E + 05	1.05E - 204	5.60E + 04
Pu239	Surrogate 7	2.41E + 04	6.66E + 03	2.90E - 10	2.43E + 05
Pu241	Surrogate 7	1.44E + 01	6.39E + 04	0.00E + 00	NA
Lead	Surrogate 7	NA	5.76E + 01	2.81E - 06	1.00E + 06
Aluminum	Surrogate 7	NA	7.08E + 03	3.45E - 04	1.00E + 06
Ra226	Surrogate 7	1.60E + 03	4.74E + 02	1.00E - 25	5.60E + 04
Aroclor-1260	Surrogate 8	7.00E + 00	7.21E - 01	0.00E + 00	NA

Table 2-5. (continued).

Constituent		Half-Life (years)	Design Inventory Concentration (C_{DI}) (pCi/kg or mg/kg)	Peak Concentration (pCi/L or mg/L)	Peak Concentration Arrival Time (years)
Am241	Surrogate 8	4.32E + 02	2.38E + 04	0.00E + 00	NA
Eu152	Surrogate 8	1.33E + 01	9.68E + 05	0.00E + 00	NA
Eu154	Surrogate 8	8.80E + 00	8.21E + 05	0.00E + 00	NA
Chrysene	Surrogate 8	3.76E + 00	2.65E - 01	0.00E + 00	NA
Zirconium	Surrogate 8	NA	6.91E + 01	3.58E-15	1.00E + 06

NA – Not Available.

2.2.1 Radioactive Progeny

To address whether radioactive progeny contribute significantly to groundwater concentrations, the assumption was made that as a worst case the activities of the daughter products were equal to the activities of the initial inventories of the parents. The resulting daughter inventory was then added to the initial design activity of the daughter radionuclides and the potential effect of the total concentration on groundwater was evaluated. If the worst case is predicted not to affect groundwater there is no need to do further evaluations. Four decay sequences were evaluated on this basis, assuming that the daughter products had sufficient half-life to be transported from the landfill to the assessment point:

1. U-234 from the initial inventory of Pu-238
2. Am-241 from the initial inventory of Pu-241
3. Np-237 from the initial inventory of Pu-241
4. Np-237 from the initial inventory of Am-241.

Predicted peak concentrations of Np-237 and U-234 are significantly increased by assuming that the activity of the daughters are equal to the activity of the parent radionuclides in the inventory, but these peak concentrations are not expected to occur for more than 500,000 years. The Np-237 and its parent inventory, which shows a relatively high peak concentration, is not expected to reach the assessment point in any quantity for at least 17,000 years, and its groundwater concentration would not be predicted to exceed 1 pCi/L for at least 150,000 years. The U-234 and its parent inventory are not predicted to reach the assessment point in any quantity for at least 14,000 years, and the peak concentration is not predicted to occur until 523,000 years. The Am-241 decays too quickly to expect any quantity to reach the assessment point. While the radioactive decay process occurs, the daughter products would be transported from the source term, reducing the source term concentration and reducing the resulting groundwater concentration. As a result, it is not possible that future U-234 and Np-237 concentrations at the assessment point will be as high as those estimated by assuming that the activity of the daughters are equal to the activity of the parent radionuclides. Therefore, the daughter products are not considered to pose a future risk. Table 2-6 presents a summary of the results.

Table 2-6. Results of selected radioactive daughter product transport simulations at maximum design recharge rate scaled to ICDF inventory of all parents.

Isotope	Isotope Specific Activity (Ci/g)	Design Inventory (kg)	Design Inventory (Ci)	Inventory with Progeny (Ci)	Inventory with Progeny pCi/kg	Peak DAF ^a (pCi/L per pCi/kg)	Peak Assessment Point Concentration (pCi/L)	Peak Assessment Point Concentration Arrival Time (Years)
Pu-238	1.71E + 01	7.97E - 03	1.37E + 02					
Pu-241	1.03E + 02	3.63E - 04	3.74E + 01					
Np-237	7.05E - 04	5.33E - 01	3.76E - 01	5.17E + 01	8.84E + 04	2.15E - 03	1.90E + 02	9.63E + 05
Am-241	3.44E + 00	4.06E - 03	1.39E + 01	5.13E + 01	8.77E + 04	0	0	0
U-234	6.24E - 03	5.65E - 01	3.53E + 00	1.40E + 02	2.39E + 05	5.41E - 07	1.30E - 01	5.23E + 05

a. Dilution/attenuation factor (DAF).

2.2.2 Sensitivity Analysis

Additional modeling scenarios were conducted to evaluate some of the parameters that are expected to have the greatest effect on the results. The sensitivity analysis focused on I-129 because that contaminant is highly mobile, a long-lived radionuclide, and is present in the design inventory at sufficient quantity to potentially pose elevated risk. In addition to the two recharge rates, alternate assessment points and screen size, and different distribution coefficients were used to simulate the fate and transport of the I-129. The alternate assessment points were located at the edge of the surface barrier (approximately 58 m from the bottom of the landfill), and 100 m from the edge of the surface barrier (approximately 158 m from the bottom of the landfill). The alternate screen length was 15 m, which is a common water production well screen length. Two different sets of distribution coefficients for the I-129 were used: one with a $K_d = 0.1$ in the waste layer and 0 elsewhere except in the clay, and the second with a $K_d = 0.1$ mL/g in all of the waste, operations, and interbed layers, and 0 elsewhere except in the clay. All sets use $K_d = 1$ mL/g in the clay layer. The results show that the I-129 concentration is most sensitive to changes in the recharge rate. The other changes generally resulted in changes of less than 10% in the assessment point groundwater concentrations. The I-129 concentration does not appear to be strongly dependent on the location of the assessment point or screen length, especially when the time frame of the modeling is considered. Table 2-7 summarizes the results and includes the results of the design fate and transport simulations for the purpose of comparison.

Table 2-7. Results of selected radioactive daughter product transport simulations at maximum design recharge rate scaled to ICDF inventory of all parents.

	Well Screen Length	Design Inventory Concentration = 1.30E + 03 pCi/kg	Recharge = 0.01 m/yr		Recharge = 0.0001 m/yr	
			Peak Undecayed DAF	Peak Concentration (pCi/L)	Peak Undecayed DAF (Ci/L per Ci/kg)	Peak Concentration (pCi/L)
I-129o	5 m	Assessment Pt. 1	8.83E + 00	1.15E + 01	9.91E - 02	1.28E - 01
I-129o	5 m	Assessment Pt. 2	9.55E + 00	1.24E + 01	1.08E - 01	1.40E - 01
I-129o	5 m	Assessment Pt. 3	7.14E + 00	9.28E + 00	7.92E - 02	1.03E - 01

Table 2-7. (continued).

	Well Screen Length	Design Inventory Concentration = $1.30\text{E} + 03$ pCi/kg	Recharge = 0.01 m/yr		Recharge = 0.0001 m/yr	
			Peak Undecayed DAF	Peak Concentration (pCi/L)	Peak Undecayed DAF (Ci/L per Ci/kg)	Peak Concentration (pCi/L)
I-129o	15 m	Assessment Pt. 1	8.48E + 00	1.10E + 01	9.49E - 02	1.23E - 01
I-129o	15 m	Assessment Pt. 2	9.10E + 00	1.18E + 01	1.02E - 01	1.33E - 01
I-129o	15 m	Assessment Pt. 3	6.96E + 00	9.05E + 00	7.72E - 02	1.00E - 01
I-129A	5 m	Assessment Pt. 1	8.13E + 00	1.06E + 01	9.09E - 02	1.18E - 01
I-129A	5 m	Assessment Pt. 2	8.80E + 00	1.14E + 01	9.89E - 02	1.29E - 01
I-129A	5 m	Assessment Pt. 3	6.57E + 00	8.54E + 00	7.27E - 02	9.45E - 02
I-129A	15 m	Assessment Pt. 1	7.81E + 00	1.02E + 01	8.71E - 02	1.13E - 01
I-129A	15 m	Assessment Pt. 2	8.37E + 00	1.09E + 01	9.38E - 02	1.22E - 01
I-129A	15 m	Assessment Pt. 3	6.41E + 00	8.34E + 00	7.08E - 02	9.21E - 02
I-129B	5 m	Assessment Pt. 1	6.84E + 00	8.89E + 00	7.72E - 02	1.00E - 01
I-129B	5 m	Assessment Pt. 2	7.40E + 00	9.61E + 00	8.40E - 02	1.09E - 01
I-129B	5 m	Assessment Pt. 3	5.53E + 00	7.18E + 00	6.17E - 02	8.02E - 02
I-129B	15 m	Assessment Pt. 1	6.56E + 00	8.53E + 00	7.40E - 02	9.62E - 02
I-129B	15 m	Assessment Pt. 2	7.04E + 00	9.15E + 00	7.97E - 02	1.04E - 01
I-129B	15 m	Assessment Pt. 3	5.39E + 00	7.01E + 00	6.02E - 02	7.82E - 02

I-129o: $K_d = 1$ mL/g in Clay, 0 elsewhere

I-129A: $K_d = 1$ mL/g in Clay, 0.1 mL/g in Waste, 0 elsewhere

I-129B: $K_d = 1$ mL/g in Clay, 0.1 mL/g in other non-Basalts, 0 elsewhere

Assessment Pt. 1 = 78 m from Waste (20 m from Edge of Cap)

Assessment Pt. 2 = 58 m from Waste (Edge of Cap)

Assessment Pt. 3 = 158 m from Waste (100 m from Edge of Cap)

2.2.3 Estimated Efficacy of Design Cover Recharge Reduction

A comparison of the apparent efficacy of the design final cover for the ICDF at the estimated background recharge rate and at the design cover recharge rate was performed to estimate the risk reduction that may be provided by the final cover. To perform this assessment, the cumulative excess carcinogenic risk, cumulative hazard index (HI) for non-carcinogens, and the total alpha-emitting radionuclide concentrations in groundwater were calculated based on the fate and transport simulation described in the preceding sections.

The comparison was made by determining the peak risk, HI, and alpha-emitter concentration in groundwater during the 1,000-year design life of the final cover. The final cover could provide up to six orders of magnitude reduction in carcinogenic risk and HI, with greater than eight orders of magnitude reduction in the concentration of alpha emitters during the 1,000-year design life of the cover. The results of the comparison are shown in Table 2-8. The cumulative risk, HI, and alpha emitter concentration are shown in figures in Appendix D.

Table 2-8. Comparison of estimated carcinogenic risk, cumulative HI, and alpha-emitter concentration in groundwater during the 1,000-year design life at the ICDF at background recharge rate and design cover recharge rate.

Risk Factor	Units	Recharge = 0.01 m/yr	Recharge = 0.0001 m/yr
Hazard Index	Unitless	3.8E00	3.9E - 06
Excess Carcinogenic Risk	Unitless	3.7E - 05	1.0E - 11
Total Alpha Emitters	pCi/L	8.0E - 06	<1.0E - 14

3. CONCLUSIONS

The fate and transport modeling conducted to support construction of the ICDF indicates that the landfill requires the surface barrier to limit recharge to meet groundwater RAOs. According to the results of hydrologic cover and the fate and transport modeling, the cover barrier is designed to prevent potentially elevated risk at the assessment point from occurring for thousands of years. A specific sensitivity analysis conducted on the fate and transport of I-129 indicated that the estimated peak concentration for the 1,000,000-yr simulation would be around 10 pCi/L at a recharge rate of 0.01 m/yr, but that the presence of the barrier reduces the estimated peak concentration by a factor of 100. Analysis of radioactive daughter products indicated that even if all of the design inventory parents were converted to Np-237, the peak concentration would not occur for over 950,000 years, and the concentration would not be expected to exceed 1 pCi/L for at least 150,000 years. No other daughter products are expected to pose a risk in the groundwater.

The design recharge rate expected to be provided by the final cover for the ICDF would provide approximately a six order-of-magnitude reduction in carcinogenic risk, non-carcinogenic HI, and concentration of alpha-emitting radionuclides over the 1,000-year design life of the final cover. This analysis indicates that the ICDF can be constructed and operated to not exceed the groundwater RAOs during the design life of the facility.

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